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TECHNICAL NOTE

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AN EVALUATION OF DETAIL WIND DATA AS MEASURED BY THE FPS-16 RADAR/SPHERICAL BALLOON TECHNIQUE

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TECHNICAL NOTE D-1572

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SUMMARY

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This report presents and evaluates a method for measuring detail winds at high altitudes with an accuracy several times better than any current operational all weather system. The method presented herein consists of tracking an aluminized spherical balloon with the FPS-16 radar, and subsequent data reduction and analysis to obtain wind data.

Two techniques for reducing tracking data to obtain wind data are presented. These consist of statistical and polynomial approaches for eliminating measurement errors in the tracking data. It is shown that average wind speeds over 50 - meter altitude intervals can be measured with a maximum RMS error of about 0.8 m/sec at altitudes where maximum wind speeds normally occur (~ 12 km at Cape Canaveral), and a maximum RMS shear error over 50 meters of 0.023 sec^{-1}.

Computer programs for data reduction were developed and are presented in outline form. A sample of data employing the polynomial smoothing technique is presented for illustration purposes, and to demonstrate the capability of the system.

SECTION I. INTRODUCTION

Measurements of wind have been made on a routine basis for many years. Continuous measurements near the ground are made with fixed anemometers, while high altitude measurements are made at some time interval, usually 12 hours apart. Detail and accurate wind measurements at altitudes above ground based instruments have been a subject of much interest for use in spacecraft design and performance studies.

Present operational measuring techniques provide methods for obtaining mean wind speeds averaged both in space and in time. These methods smooth out the small scale variations which are of importance in spacecraft design and performance analyses. The rawinsonde unit currently in use (ref. 1) on a routine basis to measure upper level winds does not provide measurements with either the accuracy or detail needed in this work. Measurements are needed with an altitude resolution of perhaps 50 meters or less and wind speed accuracy of about 1 m/sec or less.

The purpose of this report is to present an error analysis and data reduction scheme for the FPS-16 radar/spherical balloon technique, and to demonstrate the capability of the system for measuring winds and wind shears.

Numerous people contributed to the preparation of this report. Those making notable contributions were: Dr. Bruns of the Launch Operations Directorate who assisted in developing data reduction techniques; Mr. Robert Fallon of the Computation Division who made numerous suggestions regarding data reduction procedures; Mr. J. Sanderlin of the Astrionics Division who was most helpful in establishing errors in radar tracking data; and Messrs. W. W. Vaughan and D. W. Camp of the Aeroballistics Division who participated in numerous discussions and made many helpful suggestions.

SECTION II. DATA REDUCTION TECHNIQUES

A. PROCEDURE FOR EDITING TRACKING DATA TAPES

Position coordinates measured by the radar (range, azimuth, and elevation) when tracking a spherical balloon normally indicate a gradual trend with superimposed high frequency-low amplitude oscillations representing random errors inherent in the system. Occasionally, values are recorded which are not accounted for by trend nor random error. These "stray" values should be eliminated before computing wind speeds and shears. A very simple "stray value" rejection technique was devised and a program developed for the IBM 7090 computer as follows:

Observed values of r, θ, and Φ are fitted to a 9-point, first degree equation by the method of least squares. Sampling rate of tracking data is 0.1 seconds. If the residual at the mid-point of the 9-point interval is greater than three times the assumed RMS error, the point is replaced by the average value over the interval. In order to prevent including stray points in the computation of the mean, the next point immediately following the 9 points used in the curve fit is compared with the 9-point mean, and if the difference is five times greater than the assumed RMS error, the point is rejected and replaced by the mean.

More elaborate techniques could be developed for editing raw data tapes. However, this simple technique appears adequate and requires very little computer time.

B. STATISTICAL TECHNIQUE FOR ERROR EVALUATION

If F is a function of X, Y, and Z, and if they are in error by ΔX, ΔY, and ΔZ, then F will be in error by some amount ΔF which is given by the Taylor's series as (ref. 2)

$$\Delta F = F_X \Delta X + F_Y \Delta Y + F_Z \Delta Z \tag{1}$$

where:

$$F_X = \frac{\partial F}{\partial X}$$

$$F_Y = \frac{\partial F}{\partial Y}$$

$$F_Z = \frac{\partial F}{\partial Z}$$

This equation is valid only if ΔX, ΔY, and ΔZ are small compared with F_X, F_Y, and F_Z. In its derivation, it was assumed that all terms involving squares, higher powers, and cross-products of ΔX, ΔY, and ΔZ are negligible, and that higher derivatives are small in value. These assumptions are valid in determining the accuracy of FPS-16 radar tracking data as will be pointed out later. Squaring both sides of equation 1 gives:

$$\begin{aligned} \Delta F^2 &= (F_X \Delta X)^2 + (F_Y \Delta Y)^2 + (F_Z \Delta Z)^2 \\ &\quad + 2F_X F_Y \Delta X \Delta Y + 2F_X F_Z \Delta X \Delta Z + 2F_Y F_Z \Delta Y \Delta Z + \ldots \end{aligned} \tag{2}$$

Replacing each term in equation 2 by its average value

$$\begin{aligned} \sigma_F^2 &= (F_X \sigma_X)^2 + (F_Y \sigma_Y)^2 + (F_Z \sigma_Z)^2 \\ &\quad + 2(F_X F_Y \sigma_X \sigma_Y r_{XY} + F_X F_Z \sigma_X \sigma_Z r_{XZ} + F_Y F_Z \sigma_Y \sigma_Z r_{YZ} \end{aligned} \tag{3}$$

where σ denotes standard deviation, and r is the correlation between the subscripted variables. Assuming errors in X, Y, and Z are independent, equation 3 reduces to

$$\sigma_F^2 = (F_X \sigma_X)^2 + (F_Y \sigma_Y)^2 + (F_Z \sigma_Z)^2. \tag{4}$$

This equation expresses the standard deviation of the error in the function in terms of the standard deviation of the errors in the variables X, Y, and Z. The relation between the variance of the mean error in the function, $\sigma_{\overline{F}}^2$, and the variance of the function, σ_F^2, is given by

$$\sigma_{\overline{F}}^2 = \frac{\sigma_F^2}{n} \tag{5}$$

where n is the number of independent observations used in determining $\overline{F}$.

The RMS sum or difference, σ_s or σ_d, between two measurements that have an RMS of σ_1 and σ_2 is given by

$$\sigma_s^2 \text{ or } \sigma_d^2 = \sigma_1^2 + \sigma_2^2 . \tag{6}$$

The above equations will be employed in Section III to evaluate accuracies in position coordinates, winds, and wind shears as measured by the FPS-16 radar/spherical balloon technique.

C. POLYNOMIAL SMOOTHING TECHNIQUE FOR ERROR EVALUATION

A representative value of a variable that shows a systematic variation with random variations superimposed may be obtained by polynomial curve fitting procedures. A polynomial of some suitable degree can be obtained which would represent the systematic variations with the residuals representing the random variations. This technique can be applied if it is possible to distinguish, at least statistically, between the systematic and random variations. Random variations in FPS-16 radar tracking data have been established (See Section III). Therefore, this technique may be applied in reducing the data.

The first step is to compute the RMS residuals in the position coordinates from the RMS errors in tracking data (azimuth, elevation, and range) using equation 4. Next, a polynomial is fitted by the least squares method that has residuals equal to or less than those computed. The mid-point of the polynomial is the representative value of the coordinate to use for the interval over which the polynomial was determined. The RMS error of this point as calculated from a first degree polynomial is σ_X^2/N, which is the same as the RMS error obtained by the statistical approach presented in paragraph B above. The RMS error of the mid-point of higher degree polynomials is somewhat larger. For a second degree it is given by

$\sigma^2 \Big/ \left[N \left(1 - \mu_2^2 / \mu_4\right) \right]$, where μ_2 is $\Sigma X^2/N$ and μ_4 is $\Sigma X^4/N$. Errors for higher degrees will not be presented since a first degree polynomial is usually sufficient.

SECTION III. ACCURACIES OF FPS-16 MEASUREMENTS USING STATISTICAL REDUCTION TECHNIQUE

A. ACCURACY OF POSITION COORDINATES

The radar is used to measure azimuth, range, and elevation of the balloon at fixed intervals of time. Errors in these measured parameters cause errors in the wind data. It is, therefore, necessary to establish the accuracy of these measurements in order to determine accuracy of the wind data. Errors in the computed winds cannot be established any more accurately than errors in the tracking data.

It is difficult to establish accuracies for radar measurements because of the intricate features of the system and the dependence of one part of the system on another. Theoretical accuracies quoted by the manufacturer are hard to attain in practice. It is probably better to determine the accuracy of each set independently from experimental data when possible.

Levition (ref. 3) assumes an RMS accuracy of 1 yard in slant range, and 0.005° in azimuth and elevation angles. Sanderlin* and others believe that an RMS accuracy of 5 yards in slant range, and 0.01° in azimuth and elevation is more reasonable. Bruns* stated that these latter values agree well with experimental data. These latter values will be assumed in this report. A technique for estimating errors in the angular measurements from tracking data will be presented later.

Spherical coordinates are related to rectangular coordinates by the following equations

$$X = r \cos \theta \cos (\Phi - 90^{\circ}) \text{ (Positive East)} \tag{7}$$

$$Y = r \sin \theta \text{ (Positive Vertical)} \tag{8}$$

$$Z = r \cos \theta \cos \Phi \text{ (Positive North)} \tag{9}$$

where:

r = slant range (yds)

θ = elevation angle (deg)

Φ = azimuth angle (deg)

Errors in the coordinates X, Y, and Z, which result from errors in r, θ, and Φ, may

*See ACKNOWLEDGEMENTS, page 2

be evaluated by use of equation 4. The assumptions are made here that errors in r, θ, and Φ are independent of each other, i. e., not correlated, and that errors in each parameter are normally distributed. Further, it will be assumed that errors in azimuth and elevation are equal in magnitude and have the same statistical distribution. Again, according to Sanderlin and Bruns these assumptions are valid. Differentiating equations 7-9 partially with respect to r, θ, and Φ, then from equation 4:

$$\sigma_X^2 = (\sigma_r \cos\theta \sin\Phi)^2 + (r\,\sigma_\theta \sin\theta \sin\Phi)^2 + (r\,\sigma_\Phi \cos\theta \cos\Phi)^2 \quad (10)$$

$$\sigma_Y^2 = (\sigma_r \sin\theta)^2 + (r\,\sigma_\theta \cos\theta)^2 \quad (11)$$

$$\sigma_Z^2 = (\sigma_r \cos\theta \cos\Phi)^2 + (r\,\sigma_\theta \sin\theta \cos\Phi)^2 + (r\,\sigma_\Phi \cos\theta \sin\Phi)^2. \quad (12)$$

Assuming $\sigma_\theta = \sigma_\Phi = \sigma_\beta$, these equations become

$$\sigma_X^2 = (\sigma_r \cos\theta \sin\Phi)^2 + r^2\sigma_\beta^2 \left[(\sin\theta \sin\Phi)^2 + (\cos\theta \cos\Phi)^2\right] \quad (13)$$

$$\sigma_Y^2 = (\sigma_r \sin\theta)^2 + (r\,\sigma_\beta \cos\theta)^2 \quad \text{(unchanged)} \quad (14)$$

$$\sigma_Z^2 = (\sigma_r \cos\theta \cos\Phi)^2 + r^2\,\sigma_\beta^2 \left[(\sin\theta \cos\Phi)^2 + (\cos\theta \sin\Phi)^2\right]. \quad (15)$$

These equations show that errors in X and Z are a function of all three measured parameters θ, r, and Φ, and their associated errors, and that Y is a function of only two of the measured parameters, r and θ, and their associated errors. The first term in each of the equations is small in comparison to the other terms except for relatively small r. Therefore, when the slant range is large enough (about 50 km) to make the first term small, errors in the position coordinates are determined primarily by errors in the angular measurements.

A technique will now be presented for estimating errors in the angular measurements experimentally from tracking data. FIGURE 1 illustrates the position coordinates, and errors in the position coordinates, for a particular measurement. The following relationships may be obtained from FIGURE 1:

$$c^2 = d^2 + (\Delta r)^2 = (\Delta X)^2 + (\Delta Y)^2 + (\Delta Z)^2$$

$$d = r\alpha \text{ (assuming } \sin\alpha = \alpha)$$

$$\alpha^2 = (\Delta\theta)^2 + (\Delta\Phi)^2 = 2\,(\Delta\beta)^2 \quad \text{(assuming } \Delta\theta = \Delta\Phi).$$

Rearranging and substituting

$$(\Delta r)^2 = c^2 - d^2 = (\Delta X)^2 + (\Delta Y)^2 + (\Delta Z)^2 - r^2 \alpha^2$$

or $$(\Delta r)^2 = (\Delta X)^2 + (\Delta Y)^2 + (\Delta Z)^2 - r^2 \alpha^2. \tag{16}$$

As pointed out above, errors in the position coordinates are determined primarily by errors in the angular measurements (azimuth and elevation) where r is large. For this reason, any reasonable assumption regarding the RMS error for large slant ranges is acceptable. The previously assumed value of 15 feet (4.5 meters) will be used here. Errors in the angular measurements are determined using equations 4, 7-9, and 16. Values of ΔX, ΔY, and ΔZ are computed from equations 4, and 7-9; α from the above relationships; and r is obtained from tracking data. Initially, it is assumed that $\Delta\beta = 0.01$ degrees. The error in slant range may be computed from equation 16 for a large number of points. The RMS of these values is then compared with the assumed RMS value of 4.5 meters. If the computed RMS value does not agree with the assumed RMS value, then the errors in azimuth and elevation ($\Delta\beta$) must be increased or decreased by some amount and the computation repeated. Approximate errors in the azimuth and elevation angles will be obtained when the computed and assumed RMS values of Δr agree. Errors in the angular measurements were evaluated by this technique for several runs. Values obtained were very close to 0.01 degrees which agree with the value quoted by Sanderlin and Bruns.

The RMS errors in the position coordinates, given by equations 13-15, are presented graphically in FIGURES 2-4. It was assumed that $\Phi = 90°$, $\sigma_r = 15$ feet (4.5 meters), $\sigma_\beta = \sigma_\theta = \sigma_\Phi = 0.01°$, while θ assumed various values between 0 and 90 degrees. The assumption that $\Phi = 90°$ implies the condition that the balloon travels from west to east at every point as the balloon rises. This assumption is realistic since the wind generally blows from west to east during winter when the wind speeds are highest. Moreover, because of this assumption, the magnitude of the errors in the position coordinates will never exceed the maximum values given in FIGURES 2-4. As shown in these Figures, errors in Z and Y increase as the elevation angle decreases, while the error in X increases as the elevation angle increases. An inspection of equations 13-15 reveals that this is a special case which is the result of assuming $\Phi = 90°$. Therefore, these graphs are for instructional purposes only, and cannot be used, in general, to evaluate tracking data. For example, when $\Phi = 0°$, the curves would be reversed with the maximum errors occuring when $\theta = 0$ degrees instead of when $\theta = 90$ degrees as in the figures. Errors in Y will always vary with range and elevation as shown in FIGURE 3, since it is independent of Φ.

Accuracy of the position coordinates can be improved by use of equation 5. This equation shows that, if a parameter is averaged over some interval, the standard deviation of the average value of the parameter is $\sqrt{n}$ smaller than the standard deviation of the parameter before averaging. It is assumed that the n observations are independent. The time interval between independent measurements, after systematic variations were eliminated, and the time interval was found to vary between approximately 0.1 and 1.0 seconds (usually between 0.1 and 0.2 seconds).

depending upon the wind direction and speed relative to the radar. The spherical balloon used for wind measurements at Cape Canaveral rises at about 8 m/sec. At this rise rate, it takes the balloon about 3 seconds to rise a distance of 25 meters. During this time the radar makes approximately 30 measurements of the position of the balloon. Assuming these are independent, then according to equation 5, the standard deviation of the errors in the position coordinates when averaged over 25-meter altitude layers is approximately 5 times smaller than the standard deviations given by equations 13-15 . When averaging over 50-meter altitude intervals, which is equivalent to approximately 6 seconds in time, the number of independent observations is 60 and the standard deviation of the averaged position coordinates is about 7.7 times smaller than the standard deviations given by equations 13-15. RMS errors in the position coordinates averaged over 25 - and 50 - meter altitude intervals are also presented in FIGURES 2-4. A comparison of the curves show the increase in the RMS accuracy of the position coordinates as a result of averaging.

B. ACCURACY OF MEASURED WIND SPEEDS

Accuracy of the measured wind speeds in obviously determined by the accuracy of the position coordinates. The accuracy of the position coordinates presented in FIGURES 2-4 are expressed as RMS values and, therefore, equation 6 can be employed to determine the RMS accuracy of the measured wind speeds. In equation form, the RMS accuracy in wind speeds, σ_W, is given by.

$$\sigma_{W_X} = \frac{\left[\sigma_{X_2}^2 + \sigma_{X_1}^2\right]^{\frac{1}{2}}}{\Delta t} \tag{17}$$

where Δt is the time interval between the two measurements. RMS errors in the component wind speeds, obtained from the RMS tracking errors averaged over 25 - and 50 - meter altitude intervals presented in FIGURES 2 and 4, are presented as function of slant range in FIGURES 5 and 6. FIGURE 7 presents RMS errors in total wind speed found by combining σ_{W_X} and σ_{W_Z} as in equation 17. These curves represent the maximum error for the given elevation and range, but may be smaller for different azimuth angles.

Accuracy of the measured wind speeds as a function of altitude is determined by the mean wind speed (this essentially controls the slant range and elevation), and the direction of the wind relative to the radar. Therefore, successive measured wind speeds may or may not have the same accuracy. Assuming a wind blowing from the west with an average speed between the ground and 12 km (maximum wind altitude) of 40 m/sec, the slant range would be 69 km. Maximum errors in wind speeds at this slant range taken from FIGURES 5-7 are: $\sigma_{W_X} = \sigma_{W_Z} = 0.8$ m/sec averaged over 50 meters, and 1.5 m/sec averaged over 25 meters; $\sigma_W = 1.15$ m/sec averaged over 50 meters and 2.1 m/sec averaged over 25 meters. These RMS errors will seldom be exceeded at 12 km since the assumed 40 m/sec mean wind speed from the ground to this altitude represents a near extreme condition. The elevation angle in this case would be about 10 degrees.

C. ACCURACY OF MEASURED WIND SHEARS

Wind Shear S is defined as

$$S = \frac{W_2 - W_1}{Y_2 - Y_1} \quad (Y_2 > Y_1) \tag{18}$$

where: W_2 is the wind speed at altitude Y_2

W_1 is the wind speed at altitude Y_1.

From this definition, it is obvious that wind shear is a function of four variables. RMS errors in all of these variables have been determined above. Therefore, errors in wind shear which result from errors in the four variables may be determined. Using equation 4 extended to four variables, the RMS accuracy in wind shear σ_S is given by:

$$\sigma_S^2 = \left(\frac{\sigma_{W_2}}{\Delta Y}\right)^2 + \left(\frac{\sigma_{W_1}}{\Delta Y}\right)^2 + \left[\frac{\Delta W \sigma_{Y_2}}{(\Delta Y)^2}\right]^2 + \left[\frac{\Delta W \sigma_{Y_1}}{(\Delta Y)^2}\right]^2 \tag{19}$$

where:

$$\frac{\partial S}{\partial W_2} = \frac{1}{Y_2 - Y_1} = \frac{1}{\Delta Y}$$

$$\frac{\partial S}{\partial W_1} = -\frac{1}{Y_2 - Y_1} = -\frac{1}{\Delta Y}$$

$$\frac{\partial S}{\partial Y_2} = -\frac{(W_2 - W_1)}{(Y_2 - Y_1)^2} = -\frac{\Delta W}{(\Delta Y)^2}$$

$$\frac{\partial S}{\partial Y_1} = \frac{W_2 - W_1}{(Y_2 - Y_1)^2} = \frac{\Delta W}{(\Delta Y)^2}$$

σ_{W_2} = RMS accuracy of the wind speed as given by equation 17 at altitude Y_2

σ_{W_1} = RMS accuracy of the wind speed as given by equation 17 at altitude Y_1

σ_{Y_1} and σ_{Y_2} = RMS accuracy of altitudes Y_2 and Y_1 as given by equation 14.

The magnitudes of the last two terms in equation 19 are small as compared with the first two terms even for small ΔY, and become negligible for large ΔY. Under expected extreme conditions of wind shear over an altitude interval of 50 meters, the last two terms will contribute only about 1 percent to the shear error. Therefore, for purposes of graphical representation of errors in wind shears, the last two terms will be omitted. RMS errors in the component wind shears, which result from the RMS tracking errors presented in FIGURES 2 and 4, are presented in FIGURES 8 and 9. RMS errors in the vector wind shear are presented in FIGURE 10. These were computed using equation 6 and the component shears presented in FIGURES 8 and 9.

Errors in wind shears at 12 km altitude, assuming a 40 m/sec mean wind speed from the surface to 12 km altitude (slant range = 69 km) as was assumed in paragraph B above, are: $\sigma_{S_X} = \sigma_{S_Z} = 0.023 \text{ sec}^{-1}$ averaged over 50 meters, and 0.084 sec^{-1} averaged over 25 meters; $\sigma_{S_V} = 0.032 \text{ sec}^{-1}$ averaged over 50 meters, and 0.115 sec^{-1} averaged over 25 meters. These RMS errors represent the maximum which can occur at this slant range, and will be smaller for different azimuth and elevation angles.

SECTION IV. COMPUTER PROGRAMS FOR REDUCING DATA

A. POLYNOMIAL SMOOTHING TECHNIQUE

1. Convert range from yards to meters, and azimuth and elevation from degrees to radians using 0.1 second data points.

2. Compute X, Y, and Z for each point:

$$X = r \cos \theta \cos (\Phi - \tfrac{\pi}{2}) \qquad \text{(Positive East)}$$

$$Y = r \sin \theta \qquad \text{(Positive Vertical)}$$

$$Z = r \cos \theta \cos \Phi \qquad \text{(Positive North)}$$

3. Correct position coordinates X, Y, and Z for earth's curvature:

$$X_C = r_o \tan^{-1} \frac{X}{r_o + Y}$$

$$Y_C = \left[X^2 + (Y + r_o)^2 + Z^2\right]^{\frac{1}{2}} - r_o$$

$$Z_C = r_o \tan^{-1} \frac{Z}{\left[X^2 + (Y + r_o)^2\right]^{\frac{1}{2}}}$$

r_o = 6,373,334 meters = radius of earth at Cape Canaveral

4. Compute RMS Errors in X, Y, and Z as follows:

$$(\Delta X)^2 = (\Delta r \cos \bar{\theta} \sin \bar{\Phi})^2 + \bar{r}^2 (\Delta\beta)^2 \left[(\sin \bar{\theta} \sin \bar{\Phi})^2 + (\cos \bar{\theta} \cos \bar{\Phi})^2\right]$$

$$(\Delta Y)^2 = (\Delta r \sin \bar{\theta})^2 + (\bar{r}\Delta\beta \cos \bar{\theta})^2$$

$$(\Delta Z)^2 = (\Delta r \cos \bar{\theta} \cos \bar{\Phi})^2 + \bar{r}^2 (\Delta\beta)^2 \left[(\sin \bar{\theta} \cos \bar{\Phi})^2 + (\cos \bar{\theta} \sin \bar{\Phi})^2\right]$$

where the bar over a parameter denotes an average over the smoothing interval (minimum of 25 meters with 50 meters recommended).

5. Determine altitude and corresponding time for 25 - meter intervals as follows:

a. Find the first Y_C which is greater than the desired altitude.

b. Use this Y_C as the mid-point of a 41-point (81-point for 50-meter interval) least squares curve fit. Start with a first degree and increase to a maximum of 9th degree polynomial until the RMS of the residuals obtained from the curve fit is equal to or less than the computed values. If this condition never exists, use the polynomial with the smallest RMS residuals.

c. Determine desired Y from polynomial

d. Repeat a, b, and c, for X_C and Z_C.

e. Interpolate linearly between times corresponding to altitudes below and above Y to obtain time corresponding to Y.

6. Compute component wind speeds $\dot{X}_n$ and $\dot{Z}_n$, the scalar wind speed V_n, and the vertical velocity of the balloon $\dot{H}$, using the following equations:

$$\dot{X}_n = \frac{X_{n+1} - X_{n-1}}{\Delta t_{(n+1,n)} + \Delta t_{(n,n-1)}} \quad \text{(m/sec)}$$

$$\dot{Z}_n = \frac{Z_{n+1} - Z_{n-1}}{\Delta t_{(n+1,n)} + \Delta t_{(n,n-1)}} \quad \text{(m/sec)}$$

$$V_n = \sqrt{\dot{X}_n^2 + \dot{Z}_n^2} \quad \text{(m/sec)}$$

$$\dot{H} = \frac{Y_{n+1} - Y_{n-1}}{\Delta t_{(n+1,n)} + \Delta t_{(n,n-1)}} \quad \text{(m/sec)}$$

Associate wind speeds with mid-point of interval.

7. Compute direction from which wind is blowing, Ψ_n, as follows:

$$\psi_n = \tan^{-1} \frac{\dot{X}_n}{\dot{Z}_n} + \text{quadrant correction}$$

The quadrant correction is determined from the signs of $\dot{X}_n$ and $\dot{Z}_n$ as follows:

$$\left.\begin{array}{l}\dot{X}_n\ + \\ \dot{Z}_n\ -\end{array}\right\} \quad 360 - \Psi_n$$

$$\left.\begin{array}{l}\dot{X}_n\ + \\ \dot{Z}_n\ +\end{array}\right\} \quad \Psi_n + 180$$

$$\left.\begin{array}{l}\dot{X}_n\ - \\ \dot{Z}_n\ +\end{array}\right\} \quad 180 - \Psi_n$$

$$\left.\begin{array}{l}\dot{X}_n\ - \\ \dot{Z}_n\ -\end{array}\right\} \quad \Psi_n$$

8. Compute shears as follows:

$$S_{X25} = \frac{\dot{X}_n - \dot{X}_{n-1}}{25} \quad (\sec^{-1})$$

$$S_{Z25} = \frac{\dot{Z}_n - \dot{Z}_{n-1}}{25} \qquad (\sec^{-1})$$

$$S_{X50} = \frac{\dot{X}_{n+1} - \dot{X}_{n-1}}{50} \qquad (\sec^{-1})$$

$$S_{Z50} = \frac{\dot{Z}_{n+1} - \dot{Z}_{n-1}}{50} \qquad (\sec^{-1})$$

$$S_{X100} = \frac{\dot{X}_{n+2} - \dot{X}_{n-2}}{100} \qquad (\sec^{-1})$$

$$S_{Z100} = \frac{\dot{Z}_{n+2} - \dot{Z}_{n-2}}{100} \qquad (\sec^{-1})$$

$$S_{X200} = \frac{\dot{X}_{n+4} - \dot{X}_{n-4}}{200} \qquad (\sec^{-1})$$

$$S_{Z200} = \frac{\dot{Z}_{n+4} - \dot{Z}_{n-4}}{200} \qquad (\sec^{-1})$$

$$S_{X300} = \frac{\dot{X}_{n+6} - \dot{X}_{n-6}}{300} \qquad (\sec^{-1})$$

$$S_{Z300} = \frac{\dot{Z}_{n+6} - \dot{Z}_{n-6}}{300} \qquad (\sec^{-1})$$

$$S_{V25} = (S_{X25}^2 + S_{Z25}^2)^{\frac{1}{2}} \qquad (\sec^{-1})$$

$$S_{V50} = (S_{X50}^2 + S_{Z50}^2)^{\frac{1}{2}} \qquad (\sec^{-1})$$

$$S_{V100} = (S_{X100}^2 + S_{Z100}^2)^{\frac{1}{2}} \qquad (\sec^{-1})$$

$$S_{V200} = (S_{X200}^2 + S_{Z200}^2)^{\frac{1}{2}} \qquad (\sec^{-1})$$

$$S_{V300} = (S_{X300}^2 + S_{Z300}^2)^{\frac{1}{2}} \qquad (\sec^{-1})$$

Subscripts refer to a component or vector, and the altitude interval over which shears are computed. For example, S_{X25} represents the x-component of wind shear measured over a 25-meter altitude interval. Associate 25-meter shears with wind speeds at top of layer; all other shears with wind speeds at mid-point of layer. Shears are positive if absolute magnitude of wind speed increases with height.

9. Compute errors in component wind speeds by:

$$\sigma_{\dot{X}} = \frac{\left[\sigma_{X_2}^2 + \sigma_{X_1}^2\right]^{\frac{1}{2}}}{\Delta t}$$

$$\sigma_{\dot{Z}} = \frac{\left[\sigma_{Z_2}^2 + \sigma_{Z_1}^2\right]^{\frac{1}{2}}}{\Delta t}$$

$$\sigma_V = \left[\sigma_{\dot{Z}}^2 + \sigma_{\dot{X}}^2\right]^{\frac{1}{2}}$$

where: σ_X and σ_Z are RMS residuals obtained from curve fit. Subscript 2 refers to top of shear layer, and 1 to bottom of shear layer.

10. Compute errors in wind shears by:

$$\sigma_{SX}^2 = \left[\frac{\sigma_{\dot{X}_2}}{\Delta Y}\right]^2 + \left[\frac{\sigma_{\dot{X}_1}}{\Delta Y}\right]^2 + \left[\frac{\Delta\dot{X}\sigma_{Y_2}}{(\Delta Y)^2}\right]^2 + \left[\frac{\Delta\dot{X}\sigma_{Y_1}}{(\Delta Y)^2}\right]^2$$

$$\sigma_{SZ}^2 = \left[\frac{\sigma_{\dot{Z}_2}}{\Delta Y}\right]^2 + \left[\frac{\sigma_{\dot{Z}_1}}{\Delta Y}\right]^2 + \left[\frac{\Delta\dot{Z}\sigma_{Y_2}}{(\Delta Y)^2}\right]^2 + \left[\frac{\Delta\dot{Z}\sigma_{Y_1}}{(\Delta Y)^2}\right]^2$$

$$\sigma_{SV}^2 = \left[\frac{\sigma_{V_2}}{\Delta Y}\right]^2 + \left[\frac{\sigma_{V_1}}{\Delta Y}\right]^2 + \left[\frac{\Delta V\sigma_{Y_2}}{(\Delta Y)^2}\right]^2 + \left[\frac{\Delta V\sigma_{Y_1}}{(\Delta Y)^2}\right]^2$$

where: Subscripts 1 and 2 refer to the bottom and top of shear layer, respectively.

11. Output may consist of the following three files or any combination:

a. Altitude, W_X, W_Z, V, Φ, $\dot{H}$, S_{X25}, S_{Z25}, S_{X50}, S_{Z50}, S_{X100}, S_{Z100}, S_{X200}, S_{Z200}, S_{X300}, S_{Z300}, S_{V25}, S_{V50}, S_{V100}, S_{V200}, S_{V300}.

b. Altitude, σ_{WX}, σ_{WZ}, σ_V, $\sigma_{S_{X25}}$, $\sigma_{S_{Z25}}$, $\sigma_{S_{X50}}$, $\sigma_{S_{Z50}}$, $\sigma_{S_{X100}}$, $\sigma_{S_{Z100}}$, $\sigma_{S_{X200}}$, $\sigma_{S_{Z200}}$, $\sigma_{S_{X300}}$, $\sigma_{S_{Z300}}$, $\sigma_{S_{V25}}$, $\sigma_{S_{V50}}$, $\sigma_{S_{V100}}$, $\sigma_{S_{V200}}$, $\sigma_{S_{V300}}$

c. Time, X, Y, Z, SGX, SGY, SGZ, ΔX, ΔY, ΔZ, N_X, N_Y, N_Z

where:

SGY, SGX, SGZ are residuals obtained from curve fits. ΔX, ΔY, and ΔZ are computed RMS errors in X, Y, and Z. N_X, N_Y, N_Z are the degrees of the polynomials used in smoothing the position coordinates.

B. STATISTICAL TECHNIQUE

The basic difference in the statistical and polynomial smoothing techniques for reducing tracking data, is the way in which random error is eliminated from the position coordinates. Therefore, paragraph A. 5 of Section IV will change. When employing statistical smoothing this paragraph becomes:

5. Determine altitude Y, and corresponding time for 25 - meter altitude intervals as follows:

a. Compute equally weighted running means of corrected position coordinates S_C, Y_C, and Z_C, using 81 data points (smoothing altitude interval is 50 meters, with intervals overlapping).

b. Linearly interpolate X, Y, and Z found in paragraph a, and corresponding time for 25 - meter intervals.

The only other modifications and/or changes necessary are to use errors in position coordinates computed in paragraph A. 4, Section IV, in computing wind and wind shear errors in paragraphs A. 9 and A. 10, Section IV, and to eliminate SGX, SGY, SGZ, N_X, N_Y, and N_Z as part of the output in paragraph A. 11. c, Section IV.

C. EXAMPLE OF REDUCED DATA

A sample of reduced data employing the polynomial smoothing technique described in paragraph A above is presented in Tables I, II, and III. The position coordinates were smoothed using 41 points (approximately 25 - meter altitude intervals) in the curve fit procedure. Symbols used in these tables are defined in paragraph A above.

SECTION V. COMMENTS

Wind data measured by the FPS-16 Radar/Spherical Balloon Technique is several times more accurate for wind speeds and altitude resolution than rawinsonde measured winds. This is based on the conservative assumption of radar tracking errors in slant range of 4.5 meters, and 0.01° in azimuth and elevation. These improved data will be valuable for turbulence studies and as an input for establishing spacecraft design criteria. Also, the system has considerable use for real time prelaunch monitorship. Tracking data can be processed to obtain wind speeds and shears, as the balloon rises, with the aid of a modest size electronic computer, and displayed at the launch complex, or elsewhere as desired.

The techniques presented herein for reducing tracking data do not account for errors due to boresite, automatic gain control, index of refraction, nor the inability of the sphere to respond perfectly to very small scale variations in wind. With the exception of the last point, these errors are small in comparison to errors in the tracking data (azimuth, elevation, and range). Because of the finite difference procedure employed to obtain wind data, bias errors due to these sources will be reduced. However, these errors will be investigated more thoroughly. Also, errors in the radar tracking data should be established more accurately if possible. This will be the subject of a future investigation.

An examination of equations 13-15 show that the accuracy of wind data can be improved by releasing the sphere at a location where σ_X, σ_Y, and σ_Z are minimized. Releasing the sphere upwind will decrease the slant range which, in turn, will decrease errors in X, Y, and Z. Also, a release point may be chosen that will minimize the influence of θ and Φ. Because of the dependence of σ_X, σ_Y, and σ_Z on r, θ, and Φ, the accuracy of wind measurements will vary with altitude, wind direction, mean wind speed, and the release point of the sphere. Therefore, for optimum conditions, highly accurate measurements of wind are possible.

Marshall Space Flight Center and the Air Force Cambridge Research Center are jointly engaged in a developmental program which will lead to the optimization of the spherical balloon for use in detail wind profile measurements employing the FPS-16 radar. This work is expected to provide standardized specifications for spherical balloon procurements. In addition, efforts are currently underway by NASA/MSFC and the Launch Operations Center (LOC), in cooperation with the Atlantic Missile Range (AMR), to procure and establish an operational FPS-16 radar/spherical balloon facility for collection of detail wind data for design studies, prelaunch monitorship, and post flight evaluation of spacecraft. Until this system becomes available, a limited measurement program will continue as set forth in AFMTC Operational Directive 098, Annex "E" (ref. 4).

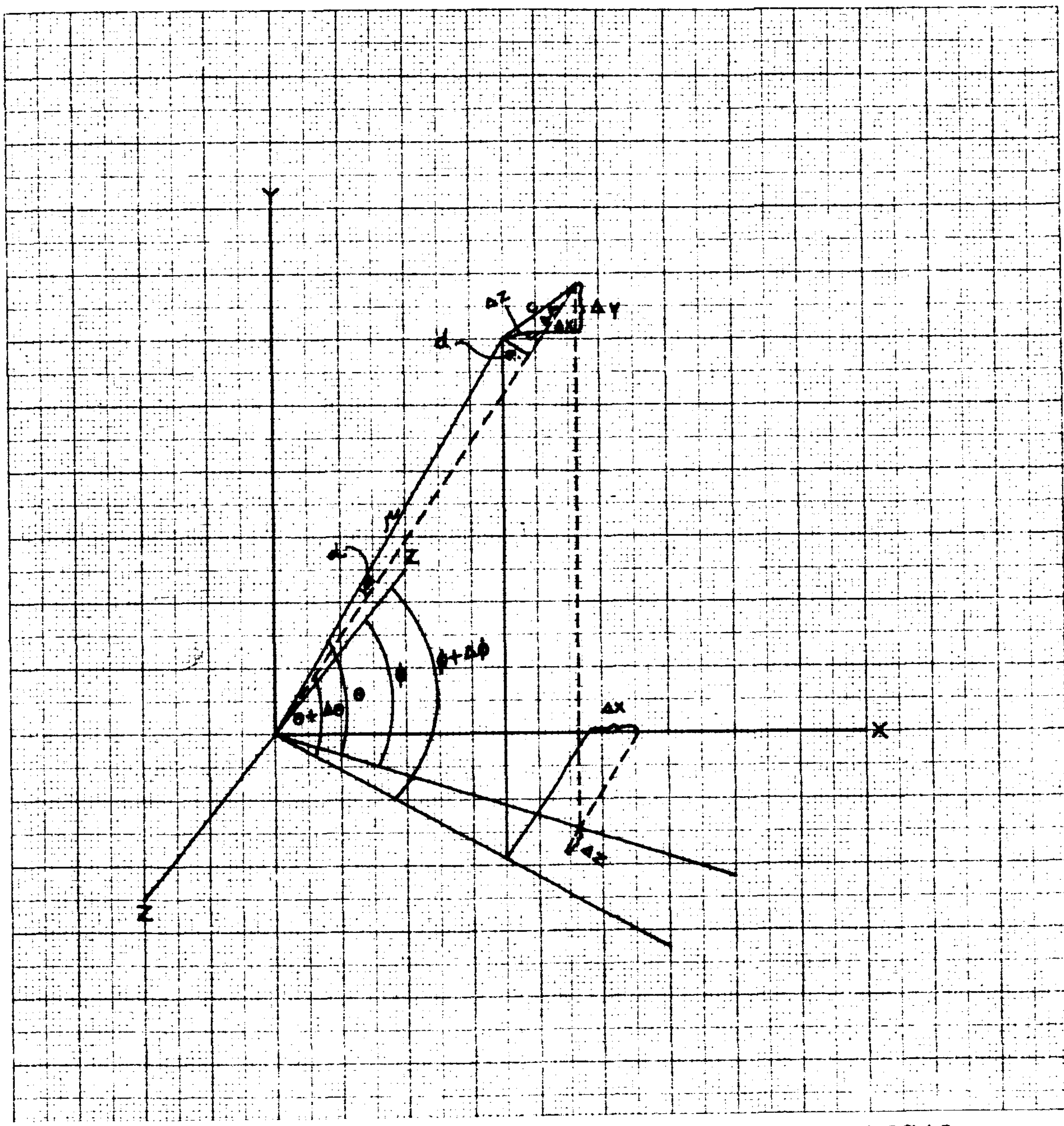

FIGURE 1. GRAPHICAL REPRESENTATION OF SPHERICAL AND RECTANGULAR POSITION COORDINATES AND THEIR ASSOCIATED ERRORS.

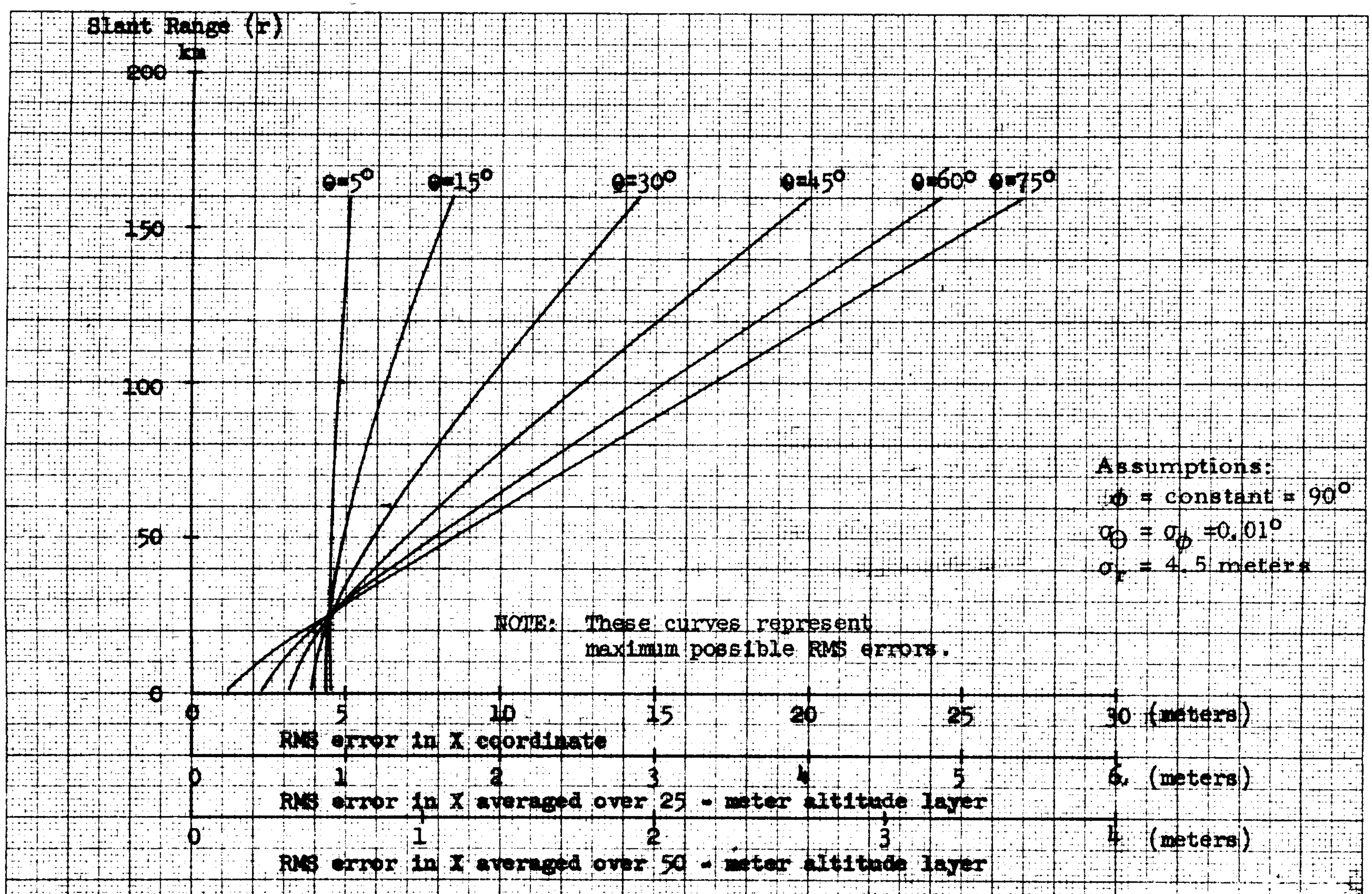

FIGURE 2. RMS ERRORS IN X COORDINATE BEFORE AVERAGING AND AFTER AVERAGING OVER 25 - and 50 - METER ALTITUDE LAYERS.

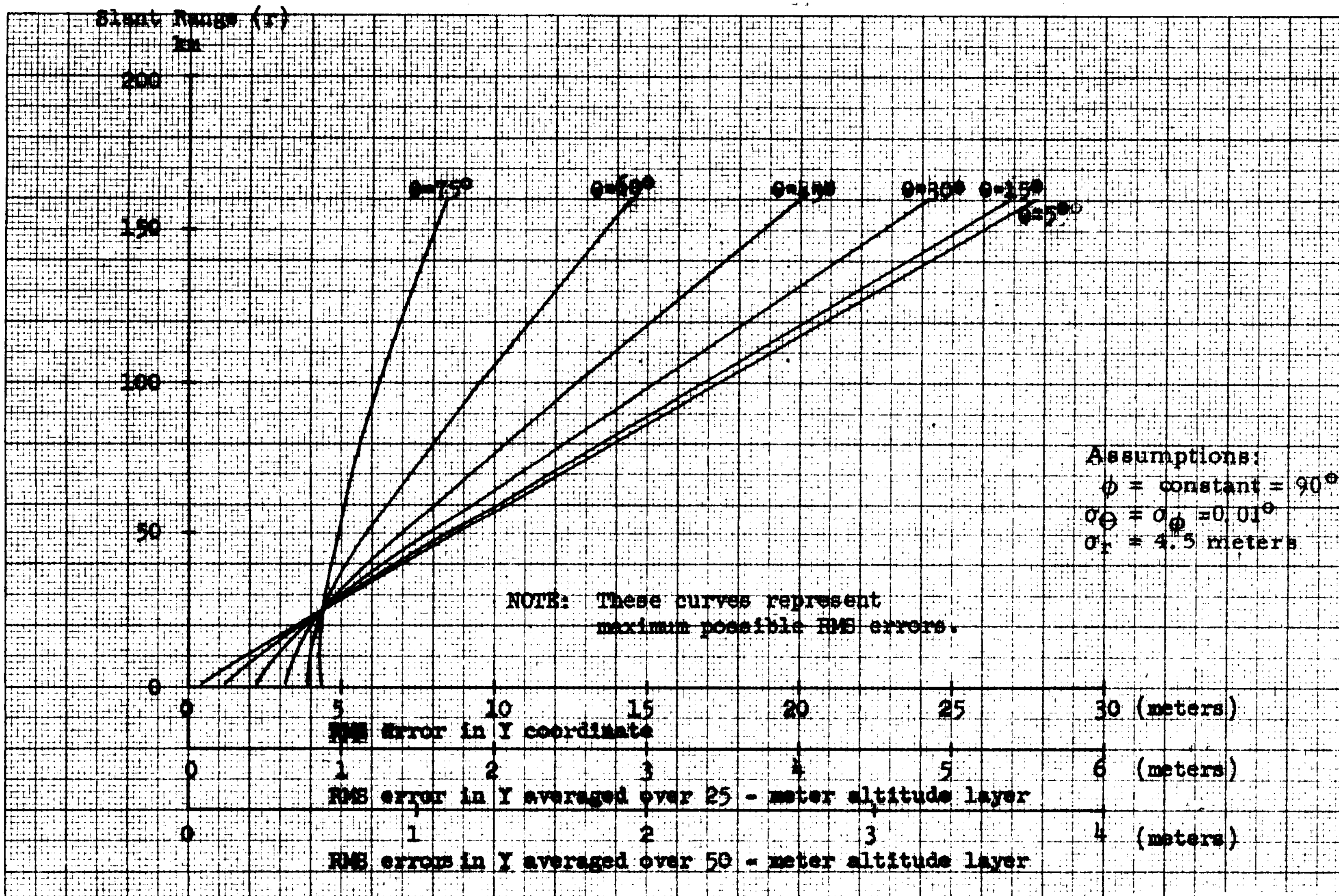

FIGURE 3. RMS ERROR IN Y COORDINATE BEFORE AVERAGING AND AFTER AVERAGING OVER 25 - AND 50 - METER ALTITUDE LAYERS.

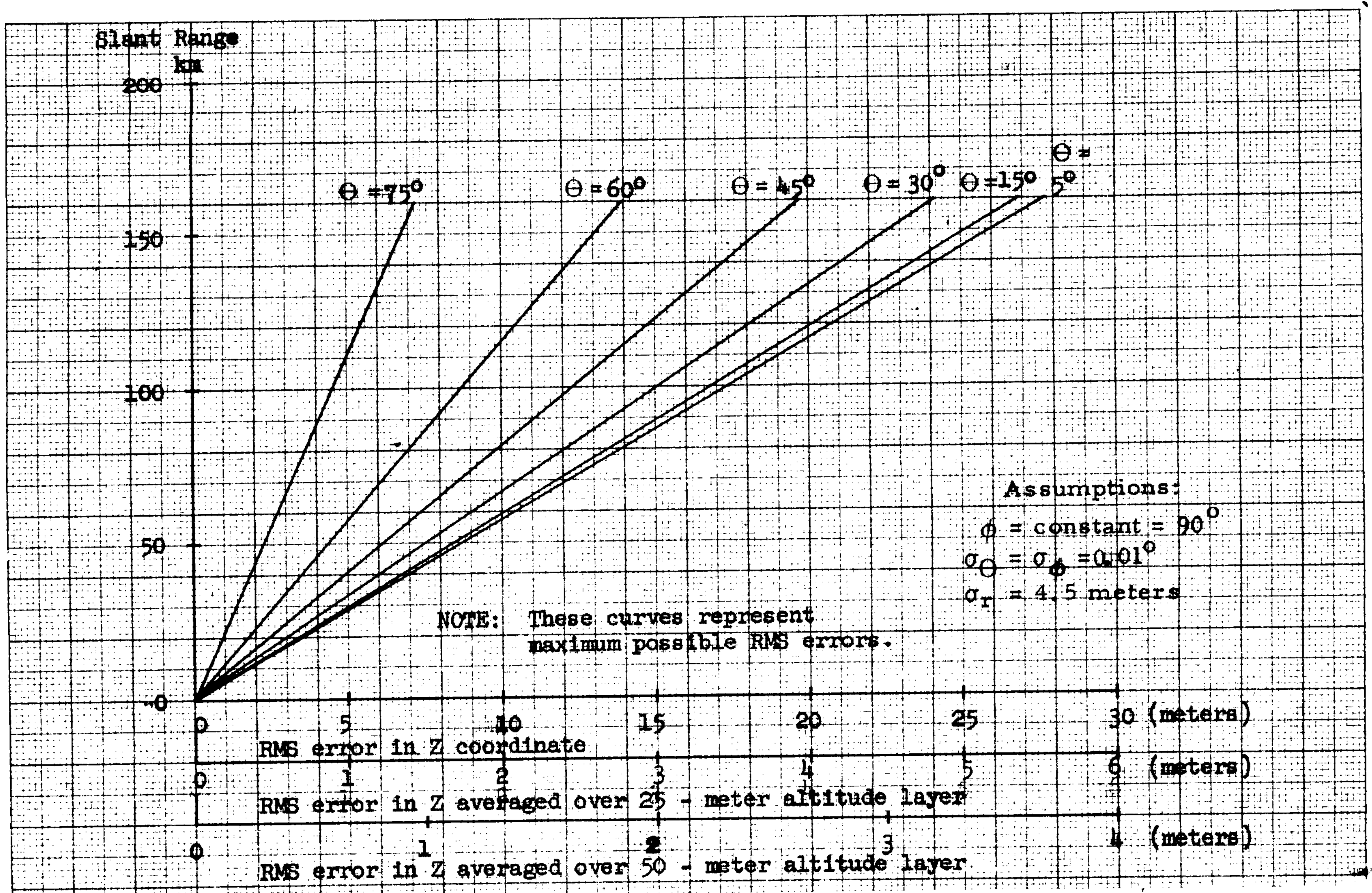

FIGURE [illegible]. RMS ERRORS IN Z COORDINATE BEFORE AVERAGING AND AFTER AVERAGING OVER 25 - AND 50 - METER ALTITUDE LAYERS.

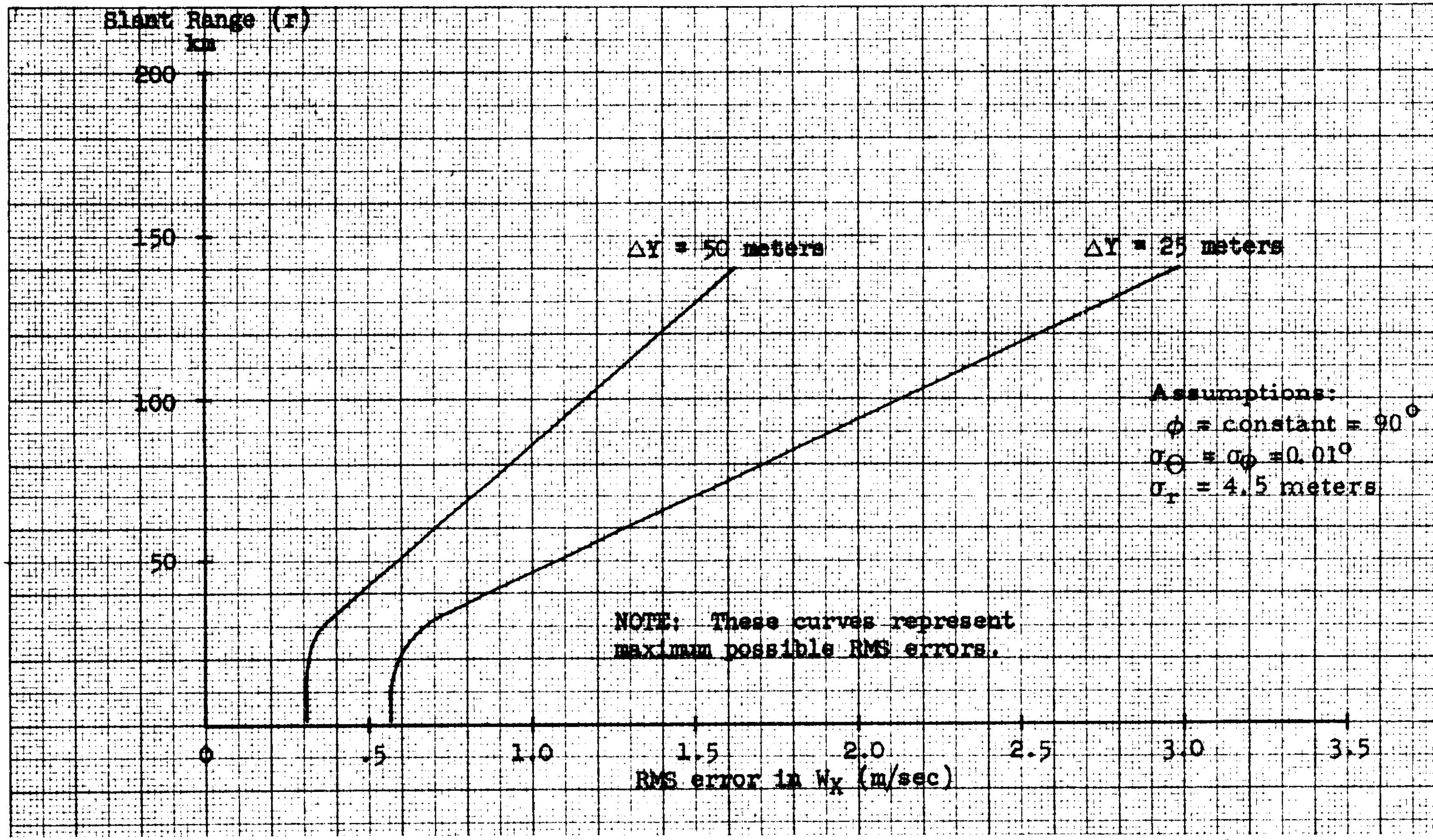

FIGURE 5. RMS ERRORS IN W_X AS FUNCTION OF SLANT RANGE FOR COORDINATE POSITIONS AVERAGED OVER 25 - AND 50 - METER ALTITUDE INTERVALS.

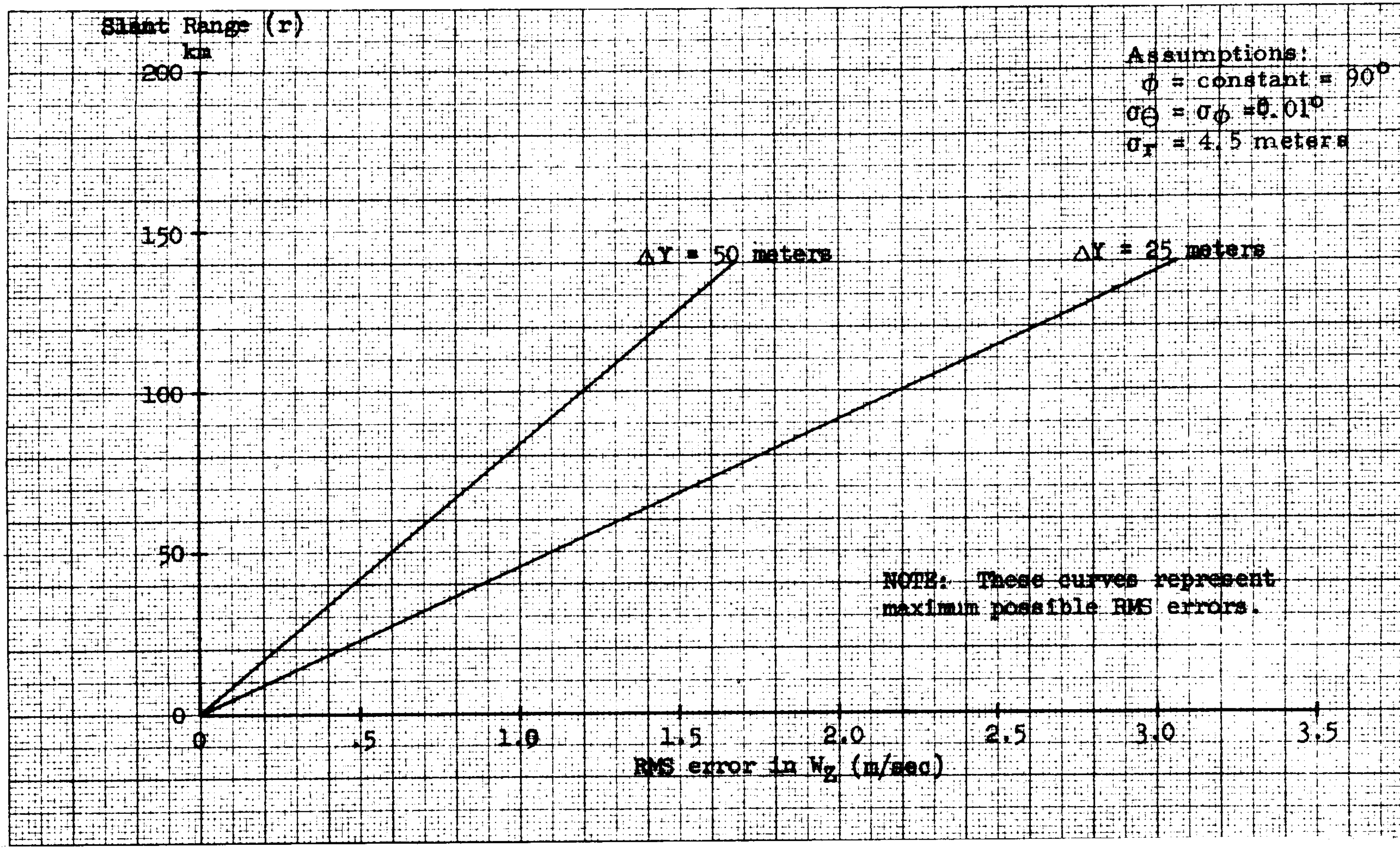

FIGURE 6. RMS ERRORS IN W_Z AS FUNCTION OF SLANT RANGE FOR COORDINATE POSITIONS AVERAGED OVER 25 - AND 50 - METER ALTITUDE INTERVALS.

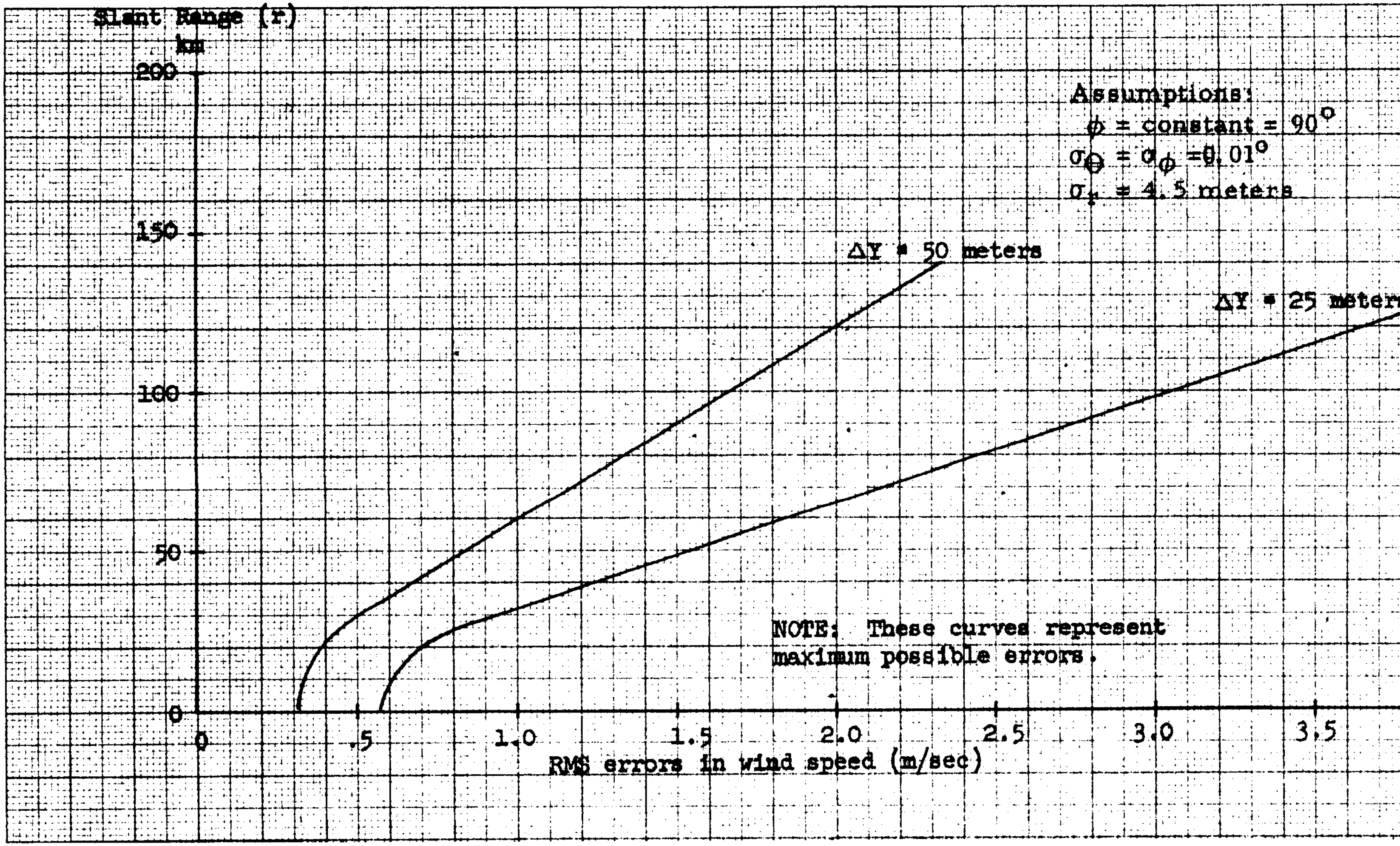

FIGURE 7. RMS ERRORS IN WIND SPEED AS FUNCTION OF SLANT RANGE FOR COORDINATE POSITIONS AVERAGED OVER 25 - AND 50 - METER ALTITUDE INTERVALS.

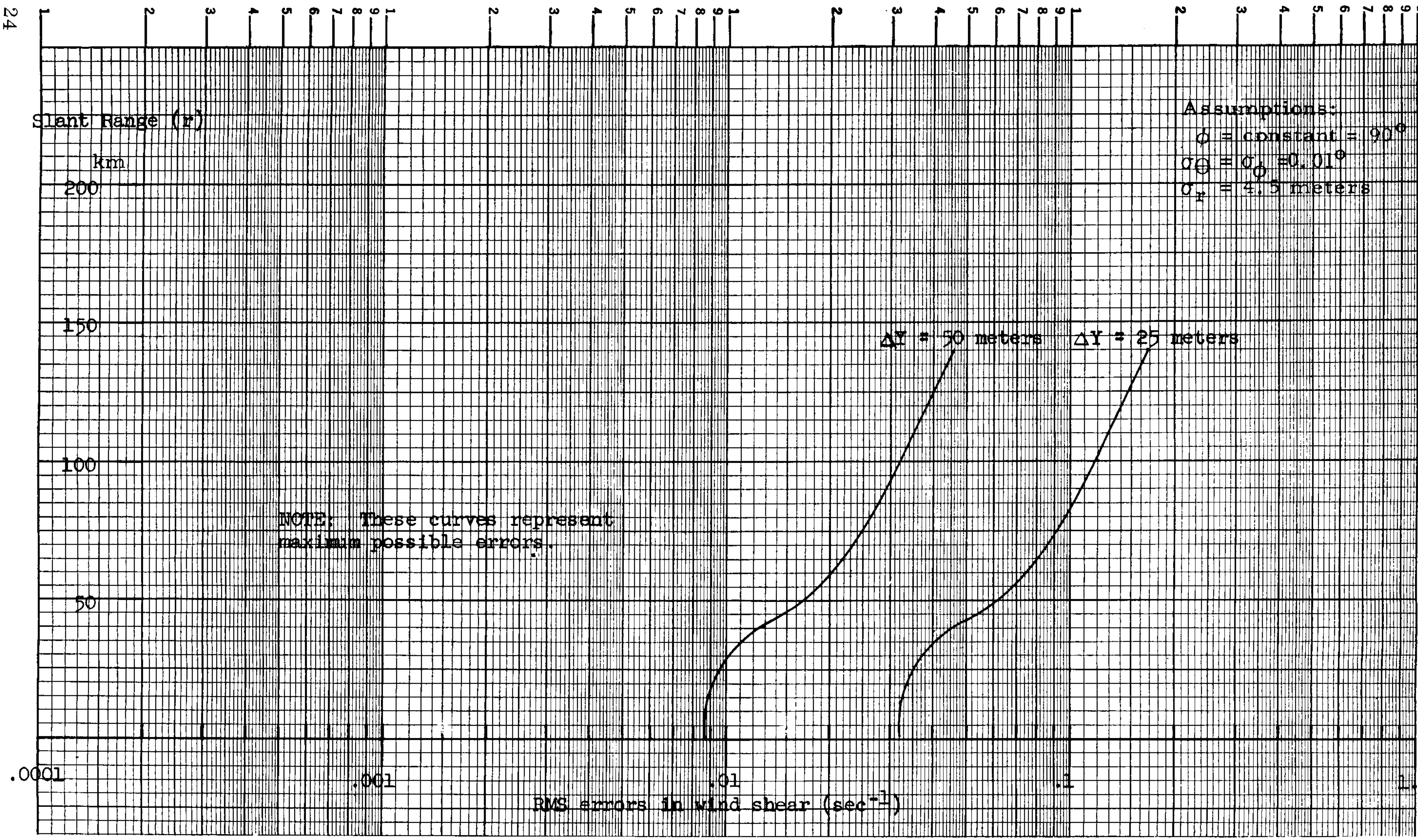

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FIGURE 8. RMS ERRORS IN THE X-COMPONENT OF WIND SHEAR AS FUNCTION OF SLANT RANGE FOR COORDINATE POSITIONS AVERAGED OVER 25 - AND 50 - METER ALTITUDE INTERVALS.

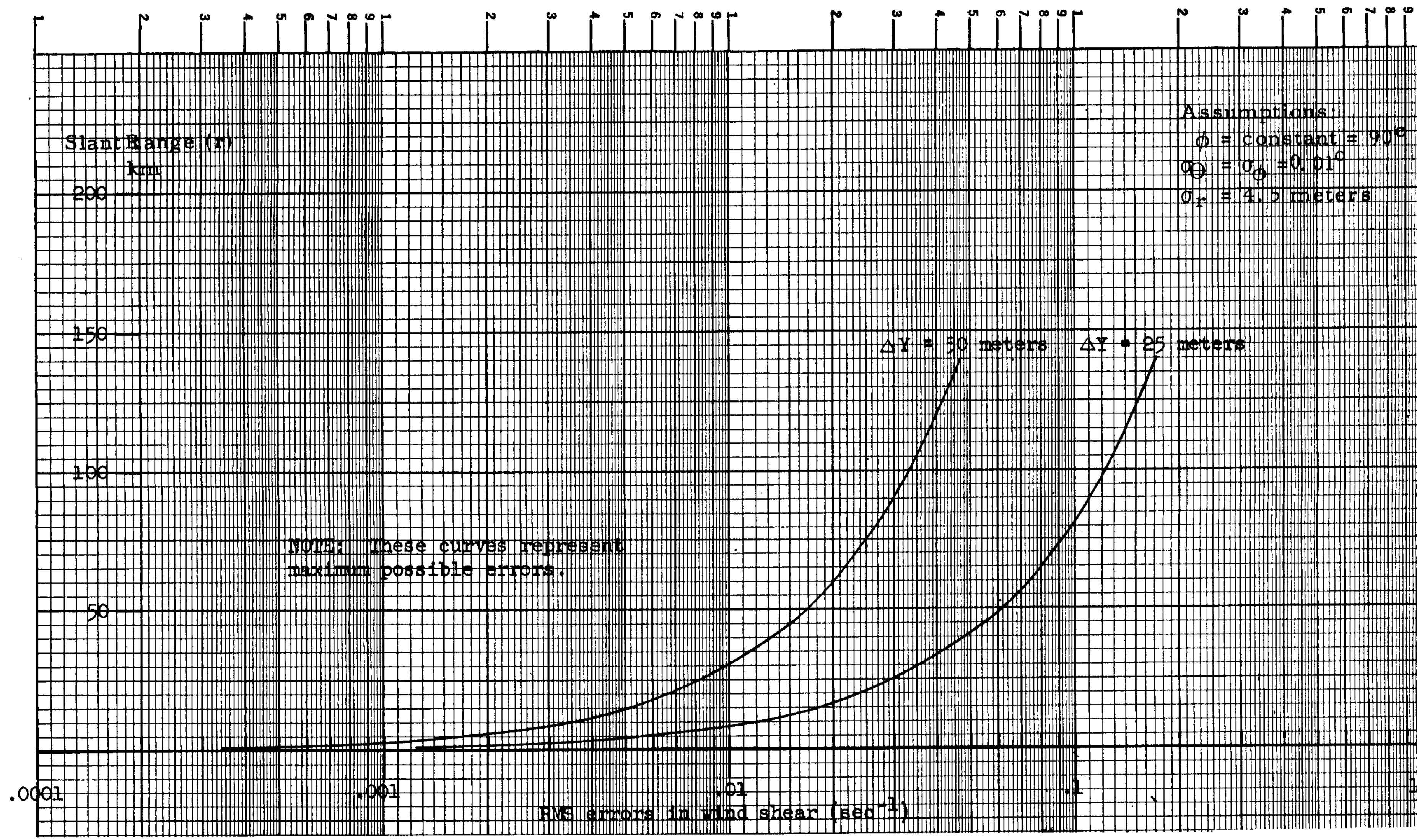
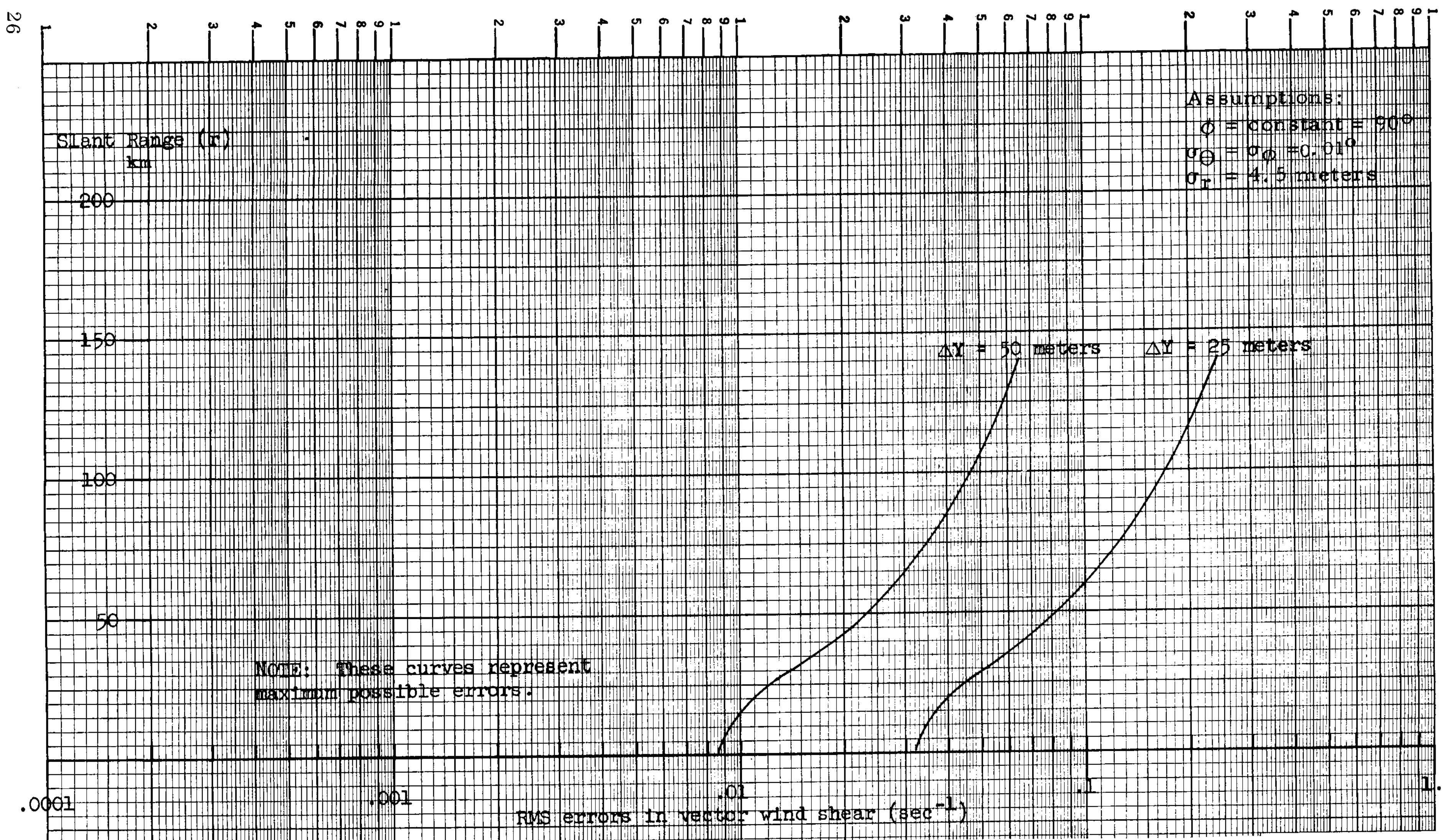


FIGURE 9. RMS ERRORS IN THE Z-COMPONENT OF WIND SHEAR AS FUNCTION OF SLANT RANGE FOR COORDINATE POSITIONS AVERAGED OVER 25 - AND 50 - METER ALTITUDE INTERVALS.



MTP-AERO-62-38

FIGURE 10. RMS ERRORS IN VECTOR WIND SHEAR AS FUNCTION OF SLANT RANGE FOR COORDINATE POSITIONS AVERAGED OVER 25 - AND 50 - METER ALTITUDE INTERVALS.

TABLE I.

FPS-16 RADAR DATA ON SPHERICAL BALLOON TEST NUMBER 98, RELEASED 2337Z, JANUARY 5, 1962

Y	WX	WZ	V	WIND DIR.	H	SX 25	SZ 25	SX 50	SZ 50	SX 100	SZ 100	SX 200	SZ 200	SX 300	SZ 300	SV 25	SV 50	SV 100	SV 200	SV 300
325.	-4.54	13.43	14.18	161.	7.63	-.008	-.009	.007	-.009	.002	.008	-.010	.019	-.009	.009	-.012	-.012	.009	.021	.012
350.	-5.08	13.18	14.12	159.	7.63	.022	-.010	.028	.020	.016	.031	-.008	.012	-.007	.010	-.024	.034	.034	.015	.012
375.	-5.92	14.45	15.61	158.	7.82	.034	.051	.024	-.071	.012	.037	.001	.008	-.009	.011	.061	.075	.039	.008	.014
400.	-6.30	16.73	17.88	159.	7.92	.015	.091	-.004	.054	.000	.028	.007	.012	-.008	.012	.093	.054	.028	.014	.014
425.	-5.72	17.14	18.06	162.	7.87	-.023	.016	-.023	-.014	-.000	.009	.002	.017	-.005	.010	.029	-.028	.009	.017	.011
450.	-5.13	16.00	16.80	162.	8.07	-.023	-.045	.004	-.037	-.002	-.006	-.003	.020	-.002	.002	-.051	-.037	-.006	.020	.003
475.	-5.90	15.30	16.40	159.	8.28	.031	-.028	.020	.003	-.007	-.004	-.008	.011	.001	.002	-.042	.020	-.008	.014	.002
500.	-6.13	16.13	17.26	159.	8.44	.009	.033	-.019	.029	-.007	.011	-.011	-.012	.001	.001	.034	.034	.013	-.016	.001
525.	-4.97	16.74	17.46	163.	8.22	-.047	.025	-.034	.019	-.017	.014	-.005	-.016	-.009	.011	.053	.039	.022	-.016	-.014
550.	-4.46	17.08	17.65	165.	7.46	-.020	.013	-.015	-.002	-.021	-.018	.001	-.013	-.015	-.019	.024	-.015	-.027	-.013	-.024
575.	-4.23	16.65	17.18	166.	7.44	-.009	-.017	-.008	-.054	-.002	-.027	-.013	-.021	-.011	-.018	-.019	-.055	-.028	-.024	-.021
600.	-4.04	14.36	14.92	164.	7.68	-.008	-.092	.010	-.053	.008	-.037	-.021	-.025	-.009	-.011	-.092	-.054	-.037	-.033	-.014
625.	-4.73	14.00	14.78	161.	7.58	.028	-.015	.025	-.019	-.009	-.055	-.012	-.025	-.014	-.007	-.032	-.031	-.056	-.028	-.016
650.	-5.27	13.42	14.42	159.	7.93	.021	-.023	-.028	-.057	-.021	-.032	-.010	-.021	-.018	-.013	-.031	-.063	-.038	-.023	-.022
675.	-3.33	11.16	11.65	163.	8.15	-.078	-.090	-.067	-.045	-.023	-.022	-.013	-.017	-.014	-.017	-.119	-.081	-.032	-.021	-.022
700.	-1.92	11.17	11.34	170.	7.79	-.056	.000	-.017	.012	-.027	-.006	-.016	-.011	-.012	-.018	-.056	.021	-.028	-.019	-.022
725.	-2.47	11.75	12.01	168.	7.75	.022	.023	.013	.033	-.017	.022	-.019	-.012	-.009	-.018	.032	.035	.028	-.023	-.020
750.	-2.55	12.82	13.07	169.	8.30	.003	.043	-.017	.031	-.011	.010	-.021	-.009	-.007	-.010	.043	.036	.015	-.023	-.013
775.	-1.61	13.31	13.41	173.	8.78	-.038	.020	-.034	-.013	-.016	-.001	-.009	.001	-.010	-.010	.043	-.037	-.016	-.009	-.014
800.	-0.83	12.18	12.21	176.	8.64	-.031	-.045	-.015	-.034	-.016	-.013	-.000	.000	-.011	-.009	-.055	-.037	-.020	.001	-.014
825.	-0.85	11.61	11.64	176.	8.42	.001	-.023	.003	-.013	-.001	-.019	-.003	-.004	-.003	-.001	-.023	-.013	-.019	-.005	-.004
850.	-0.99	11.54	11.58	175.	8.36	.006	-.003	.014	-.005	.010	-.009	-.002	-.010	-.004	-.001	-.006	-.015	-.014	-.010	-.004
875.	-1.56	11.37	11.47	172.	8.04	.023	-.007	.017	-.006	.009	-.006	.003	-.013	-.009	-.002	-.024	-.018	-.011	-.013	-.009
900.	-1.86	11.25	11.40	171.	7.69	.012	-.005	.004	-.008	.011	-.007	-.001	-.006	-.006	-.006	-.013	-.009	-.013	-.006	-.009
925.	-1.78	10.96	11.11	171.	7.44	-.003	-.011	.004	-.009	.007	-.006	-.005	-.003	-.002	-.005	-.012	-.010	-.009	-.006	-.006
950.	-2.08	10.80	11.00	169.	7.38	.012	-.006	.010	-.003	-.011	-.003	-.002	-.003	-.001	-.001	-.014	-.011	-.012	-.003	-.001
975.	-2.28	10.81	11.05	168.	7.91	-.008	.000	-.027	.003	-.020	.001	-.002	.002	-.005	.001	.008	-.027	-.020	.003	.005
1000.	-0.73	10.97	10.99	176.	8.10	-.062	.006	-.050	.005	-.014	.002	-.006	.004	.008	.001	-.062	.050	.014	.007	.008
1025.	0.21	11.07	11.07	181.	7.67	-.038	.004	-.002	.001	-.012	.009	-.012	.005	-.008	-.003	.038	.002	.015	.013	-.008
1050.	-0.66	11.02	11.04	177.	7.73	.035	-.002	.025	.012	-.001	.010	-.018	.005	-.006	-.006	-.035	.028	.010	.017	-.008
1075.	-1.07	11.68	11.73	175.	8.12	.016	.026	-.000	.019	.004	.010	-.015	-.001	-.003	-.005	.031	.019	.011	-.016	-.006
1100.	-0.65	11.99	12.01	177.	8.22	-.016	.012	-.034	.007	.021	.008	-.003	-.008	-.004	-.003	.021	.035	.023	-.008	-.005
1125.	-0.65	12.05	12.06	183.	8.42	-.052	.002	.043	.003	.019	.011	.006	-.009	.011	.002	.052	.043	-.022	-.010	-.011
1150.	1.49	11.85	11.94	187.	8.48	.033	-.008	.003	-.029	-.006	-.025	.001	-.006	.013	.000	-.034	-.029	-.026	-.006	.013
1175.	0.81	10.60	10.63	184.	7.93	-.027	-.050	-.031	-.048	.016	-.027	-.011	-.007	.010	.004	-.057	-.057	-.031	-.013	.011
1200.	-0.07	9.46	9.46	180.	7.51	-.035	-.046	.036	-.025	-.024	-.020	.019	-.005	.009	.004	-.058	-.043	-.031	-.019	.010
1225.	-0.97	9.36	9.41	174.	7.58	.036	-.004	.017	.008	.002	-.004	.012	.002	.007	-.001	-.036	.019	-.005	.013	-.007
1250.	-0.93	9.85	9.89	175.	7.54	-.002	.019	.040	.017	.032	.016	.003	.002	.006	-.004	.020	.044	.035	.004	-.007
1275.	1.05	10.19	10.25	186.	7.75	-.079	-.014	-.080	-.023	-.041	-.030	.002	.004	.003	-.006	.080	.084	.051	.005	-.007
1300.	3.09	11.02	11.44	196.	8.52	.082	.033	.042	.044	.030	.025	.006	.007	.001	-.008	.088	.061	.039	.009	-.008
1325.	3.13	12.41	12.79	194.	8.76	.002	.055	-.020	.026	.001	.013	.013	.004	.003	-.006	.056	.033	.013	.014	-.007
1350.	2.08	12.33	12.51	190.	8.35	-.042	-.003	-.039	-.018	-.020	-.002	.014	-.002	.010	-.000	-.042	-.043	-.020	-.014	.010
1375.	1.17	11.48	11.54	186.	7.92	-.036	-.034	-.019	-.031	-.015	-.022	.004	-.007	.017	.003	-.050	-.036	-.026	-.008	.018
1400.	1.13	10.78	10.84	186.	7.56	-.002	-.028	.009	-.025	-.003	-.029	-.000	-.008	.011	.004	-.028	-.026	-.029	-.008	.012
1425.	1.63	10.25	10.38	189.	7.50	.020	-.021	.014	-.027	.006	-.028	.005	-.011	.002	-.001	-.029	-.030	-.029	-.012	-.002
1450.	1.82	9.44	9.61	191.	7.83	.008	-.033	.003	-.031	.019	-.014	.002	-.007	-.005	-.007	-.033	-.031	-.024	-.007	-.008
1475.	1.79	8.70	8.88	192.	7.42	-.001	-.030	.024	-.001	.026	-.000	.002	-.007	.001	-.008	-.030	.024	.026	-.008	-.008
1500.	3.02	9.38	9.85	198.	7.66	.049	.027	.048	.031	.006	.015	.003	-.009	.004	-.006	.056	.057	.016	-.009	-.007
1525.	4.20	10.23	11.06	202.	9.16	-.047	-.034	-.011	-.031	-.002	.013	.006	-.001	.006	-.002	.058	-.033	-.013	.006	-.007
1550.	2.46	10.95	11.22	193.	7.97	-.070	.029	-.053	-.005	-.014	-.003	.007	.006	.008	.000	.075	-.053	-.014	.010	.008

Remainder of run not included because of length.

TABLE II

RMS ERRORS IN WIND SPEEDS AND SHEARS FOR TEST NUMBER 98, RELEASED 2337Z, JANUARY 5, 1962

Y	WX	WZ	V	SX 25	SZ 25	SX 50	SZ 50	SX 100	SZ 100	SX 200	SZ 200	SX 300	SZ 300	SV 25	SV 50	SV 100	SV 200	SV 300
325.	0.41	0.06	0.41	.022	.006	.009	.003	.006	.001	.003	.001	.002	.001	.022	.010	.005	.003	.002
350.	0.31	0.06	0.31	.020	.003	.012	.002	.005	.001	.004	.001	.003	.001	.021	.012	.005	.004	.003
375.	0.43	0.05	0.43	.021	.003	.010	.002	.006	.001	.003	.001	.002	.001	.021	.010	.005	.003	.002
400.	0.40	0.06	0.40	.023	.003	.012	.002	.008	.001	.004	.001	.001	.001	.024	.013	.005	.004	.002
425.	0.45	0.07	0.46	.024	.004	.016	.002	.007	.001	.003	.001	.001	.001	.024	.016	.007	.003	.002
450.	0.71	0.09	0.72	.034	.005	.014	.003	.008	.001	.002	.001	.002	.001	.034	.014	.008	.002	.002
475.	0.52	0.12	0.53	.035	.006	.019	.003	.006	.002	.002	.001	.002	.001	.036	.020	.005	.003	.002
500.	0.67	0.12	0.68	.034	.007	.013	.004	.007	.002	.002	.001	.002	.001	.034	.014	.008	.003	.002
525.	0.41	0.18	0.45	.031	.009	.014	.003	.006	.003	.003	.001	.002	.001	.032	.014	.005	.003	.002
550.	0.21	0.12	0.25	.018	.009	.009	.006	.007	.002	.004	.001	.002	.001	.020	.011	.008	.004	.002
575.	0.22	0.22	0.31	.012	.010	.007	.005	.005	.003	.003	.002	.002	.001	.016	.008	.005	.004	.002
600.	0.28	0.19	0.34	.014	.012	.007	.007	.004	.002	.004	.002	.003	.001	.018	.010	.005	.004	.003
625.	0.29	0.26	0.39	.016	.013	.010	.006	.005	.004	.003	.002	.002	.001	.021	.011	.005	.004	.003
650.	0.39	0.21	0.44	.019	.014	.011	.008	.005	.004	.003	.002	.003	.001	.024	.014	.006	.003	.003
675.	0.45	0.32	0.55	.024	.015	.011	.008	.006	.004	.002	.002	.002	.001	.028	.014	.007	.003	.002
700.	0.41	0.33	0.52	.024	.018	.013	.009	.006	.004	.003	.002	.001	.001	.030	.016	.008	.003	.002
725.	0.48	0.29	0.56	.025	.017	.013	.010	.006	.005	.002	.002	.001	.001	.031	.016	.008	.003	.002
750.	0.50	0.35	0.61	.028	.018	.013	.009	.006	.004	.003	.002	.001	.001	.033	.016	.008	.003	.002
775.	0.45	0.33	0.55	.027	.019	.014	.009	.006	.005	.003	.002	.001	.001	.033	.017	.007	.004	.002
800.	0.48	0.28	0.55	.026	.017	.011	.010	.006	.005	.003	.002	.002	.001	.031	.015	.008	.003	.002
825.	0.34	0.37	0.50	.023	.018	.012	.009	.006	.005	.003	.002	.002	.001	.030	.015	.007	.004	.002
850.	0.32	0.34	0.47	.019	.020	.009	.010	.006	.004	.003	.003	.002	.002	.027	.014	.007	.004	.002
875.	0.32	0.34	0.47	.018	.019	.009	.009	.005	.005	.003	.002	.002	.001	.027	.013	.007	.004	.002
900.	0.31	0.33	0.45	.018	.019	.009	.009	.004	.005	.003	.002	.002	.002	.026	.013	.005	.004	.003
925.	0.32	0.28	0.43	.018	.017	.008	.010	.005	.005	.002	.002	.002	.002	.025	.013	.007	.003	.002
950.	0.25	0.37	0.45	.016	.019	.010	.008	.005	.005	.002	.002	.002	.001	.025	.012	.007	.003	.002
975.	0.35	0.29	0.45	.017	.019	.009	.011	.004	.004	.002	.002	.002	.002	.025	.014	.005	.003	.003
1000.	0.36	0.37	0.52	.020	.019	.009	.009	.004	.005	.002	.002	.001	.002	.028	.012	.005	.003	.002
1025.	0.26	0.33	0.42	.018	.020	.010	.009	.004	.005	.003	.003	.002	.002	.027	.014	.005	.004	.002
1050.	0.33	0.28	0.44	.017	.017	.007	.010	.004	.005	.002	.003	.001	.002	.024	.012	.005	.003	.002
1075.	0.20	0.36	0.41	.016	.018	.008	.008	.005	.005	.003	.002	.002	.001	.024	.012	.007	.004	.002
1100.	0.22	0.31	0.38	.012	.019	.009	.011	.005	.005	.002	.003	.001	.002	.022	.014	.007	.003	.002
1125.	0.40	0.43	0.59	.018	.021	.008	.010	.005	.005	.002	.002	.002	.001	.028	.012	.007	.003	.002
1150.	0.31	0.38	0.49	.020	.023	.012	.011	.003	.005	.002	.002	.002	.002	.031	.016	.005	.003	.002
1175.	0.44	0.37	0.58	.022	.021	.008	.010	.005	.005	.002	.002	.002	.002	.030	.013	.007	.003	.002
1200.	0.26	0.36	0.44	.021	.021	.011	.009	.004	.005	.002	.003	.002	.002	.029	.015	.006	.003	.002
1225.	0.36	0.26	0.45	.018	.018	.007	.009	.006	.005	.003	.003	.002	.001	.025	.011	.008	.004	.002
1250.	0.23	0.28	0.36	.017	.015	.010	.008	.004	.006	.002	.003	.001	.002	.023	.013	.007	.004	.003
1275.	0.38	0.30	0.48	.018	.017	.008	.010	.006	.004	.003	.002	.002	.002	.024	.013	.007	.004	.003
1300.	0.32	0.43	0.54	.020	.021	.012	.009	.004	.006	.002	.003	.002	.002	.029	.015	.007	.004	.003
1325.	0.44	0.36	0.57	.022	.022	.010	.013	.006	.004	.003	.002	.002	.002	.031	.016	.007	.003	.003
1350.	0.36	0.48	0.60	.023	.024	.012	.009	.005	.007	.002	.003	.002	.002	.033	.015	.009	.004	.003
1375.	0.41	0.27	0.49	.022	.022	.010	.015	.006	.004	.003	.003	.002	.003	.031	.018	.007	.004	.004
1400.	0.37	0.57	0.68	.022	.025	.011	.007	.005	.007	.003	.003	.002	.002	.033	.014	.009	.004	.003
1425.	0.39	0.26	0.47	.022	.025	.011	.016	.006	.005	.004	.004	.002	.002	.033	.019	.008	.006	.003
1450.	0.41	0.56	0.69	.023	.025	.012	.011	.005	.008	.003	.004	.002	.003	.034	.016	.009	.005	.003
1475.	0.46	0.47	0.66	.025	.029	.011	.015	.007	.008	.003	.003	.002	.002	.038	.019	.011	.005	.003
1500.	0.38	0.50	0.63	.024	.028	.015	.019	.006	.009	.003	.004	.002	.002	.037	.024	.011	.005	.003
1525.	0.61	0.80	1.01	.029	.038	.012	.017	.007	.008	.003	.003	.002	.002	.048	.020	.010	.004	.002
1550.	0.45	0.66	0.80	.031	.042	.015	.020	.006	.008	.003	.004	.002	.002	.052	.026	.010	.005	.003

Remainder of run not included because of length.

TABLE III

FPS-16 RADAR DATA ON SPHERICAL BALLOON TEST NUMBER 98, RELEASED 2337Z, JANUARY 5, 1962

Y	TIME	X	Z	SGX	SGY	SGZ	DEL X	DEL Y	DEL Z	NX	NY	NZ
325.	2252.098	1465.16	-154.46	1.70	0.53	0.24	4.44	1.02	0.54	1	1	4
350.	2255.422	1449.47	-110.11	1.96	0.53	0.23	4.43	1.10	0.42	1	1	3
375.	2258.654	1431.84	-68.08	1.06	0.27	0.29	4.42	1.19	0.32	1	1	4
400.	2261.820	1411.60	-17.70	1.93	0.45	0.25	4.40	1.27	0.25	1	1	6
425.	2264.969	1392.04	37.55	2.26	0.50	0.26	4.37	1.36	0.27	1	1	5
450.	2268.172	1375.30	91.15	2.13	0.88	0.39	4.34	1.44	0.37	1	1	4
475.	2271.166	1360.26	136.71	3.79	1.44	0.49	4.30	1.52	0.49	1	1	3
500.	2274.207	1339.66	183.51	2.26	0.77	0.63	4.25	1.61	0.64	1	1	2
525.	2277.087	1323.94	232.22	1.07	0.55	0.51	4.19	1.68	0.78	1	1	3
550.	2280.289	1309.46	285.33	1.05	0.44	0.87	4.13	1.75	0.93	1	1	2
575.	2283.789	1294.07	346.67	0.93	0.64	0.66	4.06	1.82	1.12	1	1	2
600.	2287.011	1281.06	397.29	1.04	0.63	1.22	3.99	1.88	1.26	1	1	2
625.	2290.301	1267.79	440.20	1.57	0.78	1.05	3.91	1.95	1.38	1	1	1
650.	2293.603	1249.85	489.57	1.61	0.90	1.23	3.83	2.01	1.52	1	1	2
675.	2296.608	1234.55	524.86	1.90	0.98	0.84	3.76	2.07	1.61	1	1	1
700.	2299.735	1229.42	558.01	2.26	1.05	1.50	3.70	2.12	1.70	1	1	1
725.	2303.030	1222.19	596.59	1.78	1.07	1.94	3.63	2.16	1.78	1	1	1
750.	2306.185	1213.50	633.81	2.14	0.81	1.08	3.56	2.21	1.87	1	1	1
775.	2309.053	1206.82	673.80	2.46	0.80	0.84	3.48	2.25	1.96	1	1	1
800.	2311.881	1204.33	709.64	1.37	0.58	1.50	3.42	2.29	2.03	1	1	1
825.	2314.842	1202.00	744.30	1.28	0.61	1.36	3.36	2.32	2.09	1	1	1
850.	2317.821	1199.30	778.60	1.44	0.65	1.56	3.30	2.35	2.16	1	1	1
875.	2320.823	1196.08	813.31	1.45	0.79	1.51	3.24	2.38	2.21	1	1	1
900.	2324.041	1189.62	849.30	1.39	0.68	1.46	3.18	2.41	2.27	1	1	1
925.	2327.328	1184.00	886.49	1.43	0.98	1.51	3.11	2.44	2.33	1	1	1
950.	2330.757	1177.69	922.93	1.68	0.56	1.16	3.04	2.46	2.39	1	1	1
975.	2334.099	1169.92	959.64	0.85	0.85	2.02	2.98	2.49	2.45	1	1	1
1000.	2337.079	1163.25	991.26	1.41	0.87	1.44	2.92	2.52	2.49	1	1	1
1025.	2340.275	1165.40	1027.37	2.05	0.83	1.12	2.87	2.53	2.53	1	1	1
1050.	2343.598	1164.60	1063.44	0.91	0.69	1.60	2.82	2.55	2.58	1	1	1
1075.	2346.741	1161.16	1098.64	0.64	0.62	1.45	2.77	2.57	2.62	1	1	1
1100.	2349.755	1158.04	1135.37	0.85	0.54	1.53	2.71	2.58	2.66	1	1	1
1125.	2352.821	1157.18	1171.55	1.17	0.79	1.20	2.66	2.60	2.70	1	1	1
1150.	2355.692	1161.92	1206.89	2.24	1.16	2.02	2.63	2.60	2.73	1	1	1
1175.	2358.719	1165.95	1241.44	1.42	1.10	1.88	2.59	2.61	2.75	1	1	1
1200.	2361.997	1167.03	1273.72	1.67	0.89	1.16	2.55	2.63	2.78	1	1	1
1225.	2365.376	1165.49	1304.40	0.98	0.75	1.45	2.51	2.64	2.80	1	1	1
1250.	2368.597	1160.59	1335.52	1.71	0.65	1.27	2.46	2.66	2.83	1	1	1
1275.	2372.003	1159.35	1369.68	1.17	0.84	1.15	2.42	2.67	2.86	1	1	1
1300.	2375.053	1167.35	1401.32	1.72	0.73	1.49	2.40	2.67	2.87	1	1	1
1325.	2377.871	1177.48	1434.33	1.48	1.80	2.23	2.38	2.68	2.89	1	1	1
1350.	2380.758	1185.20	1472.11	1.86	1.28	1.38	2.35	2.68	2.91	1	1	1
1375.	2383.863	1189.91	1508.22	1.57	1.90	1.83	2.32	2.68	2.94	1	1	1
1400.	2387.068	1192.59	1544.55	1.81	0.87	0.96	2.29	2.69	2.95	1	1	1
1425.	2390.474	1197.37	1579.47	1.89	2.04	3.26	2.27	2.69	2.97	1	1	1
1450.	2393.739	1203.45	1612.92	1.91	1.63	1.45	2.24	2.69	2.99	1	1	1
1475.	2396.857	1209.01	1639.70	1.86	1.48	1.40	2.22	2.70	3.00	1	1	1
1500.	2400.481	1215.50	1671.55	2.41	2.79	2.85	2.21	2.71	3.00	1	1	6
1525.	2403.389	1228.75	1700.96	1.69	2.07	2.98	2.19	2.71	3.01	1	1	1
1550.	2405.939	1238.44	1727.41	2.32	2.94	3.30	2.18	2.72	3.02	7	8	6

Remainder of run not included because of length.

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